The Influence of Climate Variation and Change on Structure and Processes in Nearshore Vegetated Communities of Puget Sound and other Northwest Estuaries

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Abstract
The effects of climate change on coastal systems needs study because of the importance of these systems to fisheries resources and the vulnerability of these systems to climate variations. Doubling of the CO_2 could increase estuarine and coastal productivity, carbon transport among systems, and carbon export to the deep ocean. Increased temperature could also increase system respiration, increasing CO_2 release. We have been investigating the potential for variations in ocean temperature and carbon dioxide to affect nearshore vegetated communities in the Pacific Northwest. Experimental studies as well as long-term monitoring suggest that these communities can and will respond to climate changes and that alterations in their functions may impact fisheries resources. In addition, we have been examining how coastal systems might act as sinks for carbon, and how to monitor these sinks. Variability in the flux of carbon among coastal systems and loss to export and other potential large sinks is in need of study to resolve how these system might act in terms of a global carbon sink. Strategies for enhancing carbon sequestration, such as through restoration of degraded coastal wetland systems, should also be investigated.

Introduction
In this paper we present findings on the response of benthic primary producers in Puget Sound and other Pacific Northwest coastal and estuarine systems to changes in temperature and CO_2. Climate change is likely occurring and is probably forced by input of carbon dioxide primarily from the burning of fossil fuels (Houghton and others 1995). The effects of climate change on coastal systems needs study because of the importance of these systems to fisheries resources and the vulnerability of these systems to climate variations. Climate variability over decadal scales is documented and is used to explain major shifts in salmonid abundance in the Pacific Northwest and Alaska (Francis and others 1998). However, ecosystems in Northwest estuaries remain poorly studied relative to climate change.

A recent national summary of climate change and ocean conditions by the National Oceanographic and Atmospheric Administration (Boesch and others 2000) states that there are five key issues related to coastal areas and marine resources, including:

- Shoreline erosion and human communities
- Threats to estuarine health
- Coastal wetland survival
- Coral reef die-offs
- Stresses on marine fisheries.

The report concludes that the issues of greatest importance in the Pacific Northwest are:

- Changes in timing of freshwater resources
- Added stresses on salmon
- CO_2 and summer drought effects on forests
- Sea-level rise impacts on coastal erosion.

We have been investigating the potential for variations in ocean temperature and carbon dioxide to affect nearshore vegetated communities in the Pacific Northwest (Thom 1990, 1996; Thom and Albright 1990).

Experimental studies as well as long-term monitoring suggest that these communities will respond to climate change and that alterations in their functions may impact fisheries resources.

Primary Producers and Carbon Sources in Puget Sound and other Pacific Northwest Systems

The major types of primary producers in Puget Sound and coastal estuaries in the Pacific Northwest include phytoplankton, benthic microalgae, seaweeds, kelp, seagrasses, and tidal (fresh, brackish, salt) marshes. Other carbon sources along coastal margins include terrestrial, estuarine, and marine sources, with the most important external sources of carbon include diffusion of CO_2 (dissolved), death of marine producers (particulate), and terrestrial and estuarine debris (dissolved and particulate) (Valiela 1984). The contribution of terrestrially derived carbon and marine-derived carbon varies along the coastal margin, depending largely upon the volume of riverine input and distance from the source. Although not well studied, data from Grays Harbor estuary indicate that terrestrial carbon represents a major source to the estuary (Thom 1981). The Columbia River estuary receives large amounts of carbon from production in the reservoirs created by the dams on the river (Sherwood and others 1990). Internal sources of dissolved and particulate carbon include recycling of dead particles, exudation from producers, release from broken cells, and excretion by consumers (Valiela, 1984). During periods of upwelling, which are common in summer along the Northwest coast, resuspension of very light particulate organic carbon becomes another potential carbon source.

Results from Studies in the Pacific Northwest

Sea Level Rise

Sea level rise threatens not only the existence of coastal communities but also the health and viability of coastal ecosystems. Perhaps the most notably threatened system is tidal marshes. Because tidal marshes occupy a relatively narrow elevation range at the interface of the land the sea, small changes in mean sea level can have devastating effects on their distribution. Flooding of tidal marshes because of a rising sea level has resulted in substantial and continuing losses of marshes in Louisiana and Maryland (Boesch and others 2000).

The standard method for evaluating whether sea level rise is threatening tidal marshes is through comparison of the accretion rate of marshes with the relative rise rate of the sea. Using Cs^{137} as a marker, we found that most marshes are presently keeping pace with sea level rise in the Pacific Northwest (Thom 1992). Perhaps the most vulnerable marshes are those in central and lower Puget Sound where relative sea level rise exceeds the global rate. The marshes depend on a steady supply of sediments and nutrients to support accretion. If these were cut off through shoreline armoring and watershed development, the marshes in southern Puget Sound would predictably succumb to rising sea level.

Temperature Variations

There is little doubt that all of the estuarine and marine plants respond in a similar manner physiologically to temperature. Intertidal plants, such as tidal marshes, may be less susceptible because of their ability to withstand wide temperature changes. However, drying induced by warmer climate may induce water stress through drying of soils, and concentration of mineral salts. Submerged plants such as eelgrass and kelp (*Nereocystis luetkeana*), may be the most susceptible to warmer conditions.

Our experiments with eelgrass (*Zostera marina*) indicate that Pacific Northwest estuarine system processes are vulnerable to temperature variations. We found a strong response of eelgrass photosynthetic rate as well as respiration rate with varying temperature. Photosynthesis peaked at about 12^{o}C (Figure 1). Respiration rate increased linearly over the range of temperatures tested. We used a ratio of photosynthesis to respiration (P:R) as an indicator of the health of the plant relative to temperature; with a ratio above one indicating net production (growth) and a ratio below one indicating net respiration (potential death). Our data showed that although photosynthesis peaked at 12^{o}C, the P:R ratio was above 1 between about 6 and 16 ^{o}C (Figure 2). The greatest P:R occurred between about 6 and 10 ^{o}C, indicating that eelgrass does best within a relatively narrow temperature range. Eelgrass does occur in areas, such as quiescent bays, where summer temperatures can exceed 10 ^{o}C for extended periods during summer low tides. However, sustained high temperatures probably stress the plants. Under a warmer climate, water temperatures may be higher on average, which may cause greater warming in summer and further stress on the plants. Eelgrass ranges into warmer regions south of the Pacific Northwest. However, the genetics and phenology of these warm water populations probably differs substantially from those in the Northwest. We do not expect elimination of eelgrass from the Pacific Northwest with a warming climate unless the warming occurs so rapidly to as to not allow for northward expansion of these southern populations or adaptation of local populations.

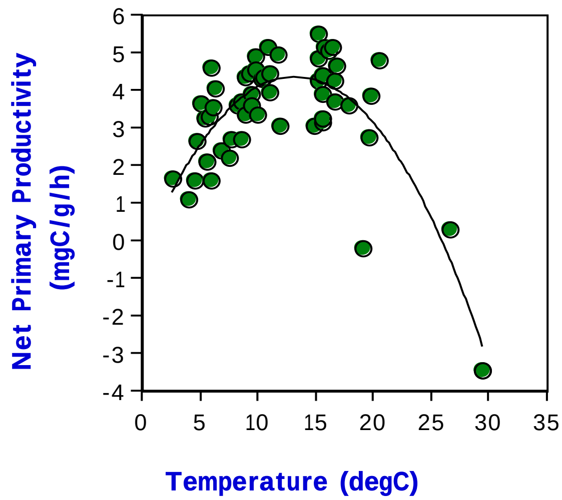

Figure 1 Experimental effects of temperature on net productivity rate of eelgrass.

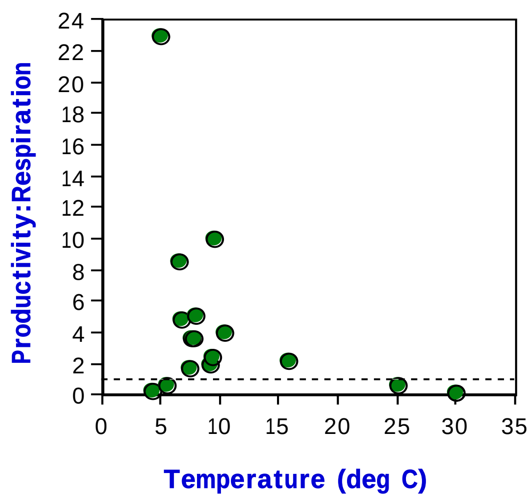

Figure 2 Effects of temperature on eelgrass productivity to respiration ratio.

Carbon Dioxide

Experiments conducted suggest CO_2 limitation in eelgrass and bull kelp (Thom 1996). A series of short-term experiments was conducted at Battelle/Marine Sciences Laboratory, which evaluated the effect of CO_2-enriched seawater on the photosynthetic rate of mudflats, eelgrass, and bull kelp. Mudflats contain dense concentrations of epibenthic diatoms, and can have relatively high NPP (actually net community production because animals and bacteria are included in the mud cores).

In single dose experiments: (1) mudflats did not show a significant response; (2) eelgrass showed a significant increase in one experiment and no effect in the second experiment; and, (3) kelp NPP was approximately doubled by the enrichment. A serial enrichment showed a rise in NPP for eelgrass and kelp up to a saturation point. It appeared, in these preliminary experiments, that both species were CO_2-limited. Autotrophs on mudflats may not be, but this system is more problematic to evaluate due to the high amount of respiration associated with the sediments.

Climate Variability and Ecosystem Processes

An increase in the degree of variability may affect fundamental processes like benthic primary production, reproduction, and respiration. Our data suggest that increased temperature variation may destabilize ecosystem primary productivity as it is now developed in these systems. For example, increasing temperature range at marine sites may result in a shift to species that are more tolerant of wider temperature variations, and vice versa. Based on data from studies of benthic primary productivity in benthic plant assemblages in several Pacific Northwest coastal systems (Grays Harbor estuary, Neah Bay, Padilla Bay, Central Puget Sound sites, Seahurst bight, Puyallup River estuary), it appears that annual temperature range roughly stratifies the various systems (Figure 3). Assemblages in these systems included rockweed (*Fucus* spp.), ulvoids (e.g., *Ulva* spp.), massive brown algae (e.g., *Costaria costata*), eelgrass, Japanese eelgrass (*Zostera japonica*), sediment microalgae, *Enteromorpha prolifera*, gravel (e.g., benthic diatoms), and bull kelp. It appears that low annual temperature range is correlated with low annual NPP. Intermediate temperature range has the greatest NPP, and where temperature range is greatest, there is a lower (intermediate) NPP. The systems with low annual range in temperature include marine systems such as Neah Bay. The highly variable systems include quiet bays such as Padilla Bay in northern Puget Sound. Intermediate sites are primarily in central Puget Sound.

Because processes such as nutrient flux from the sediments are tied to other benthic processes such as NPP, there may be ramifications on nutrient cycling as a result of temperature changes also. Our data on inorganic nitrogen release from sediments in Puget Sound show that as NPP increases apparent flux rates decrease (Figure 4). This may be partially due to the greater uptake rate associated with higher NPP (Thom and others 1994). Benthic respiration, which is highly dependent on temperature, is also correlated with nutrient flux rates. As respiration increases so does the flux of ammonia into the water column (Figure 4).

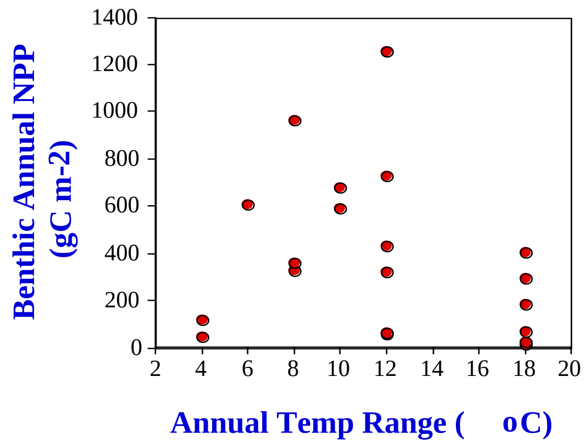

Figure 3 Relationship between annual water temperature range and benthic annual primary productivity for a variety of coastal and estuarine systems in the Pacific Northwest.

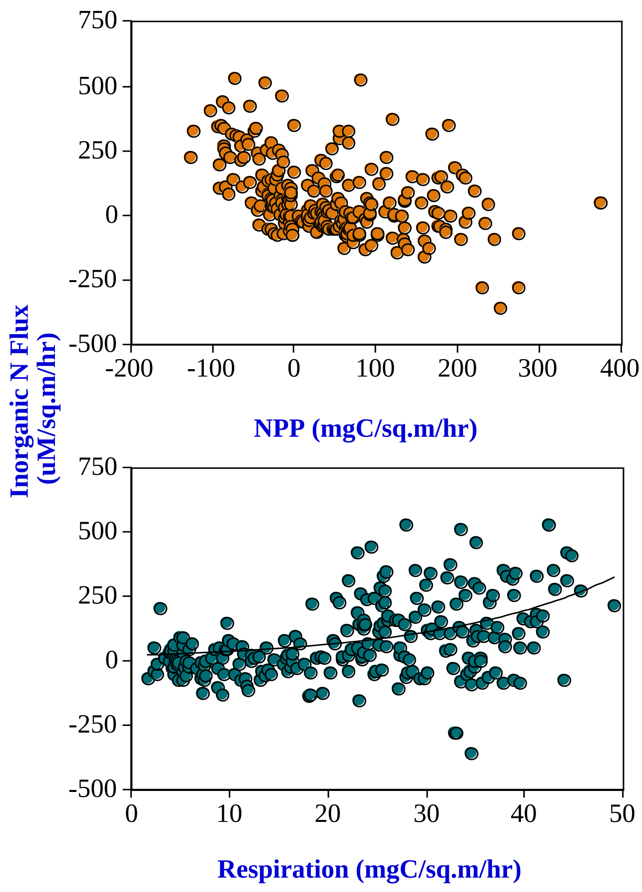

Figure 4 Relationship between benthic net primary productivity and respiration and total inorganic nitrogen flux rate from sediments (replotted from Thom and others 1994).

Conclusion

There is a clear need to focus investigations on the potential effects of a warmer and CO_2-rich environment on Puget Sound's nearshore ecosystem. Experimental data as well as field studies strongly indicate that temperature is a major factor controlling benthic primary production, respiration, and community production in Pacific Northwest estuarine ecosystems. A shift in temperature will predictably affect these processes. The actual amount of effect, the complexities of change and the ultimate impact on fisheries resources are unquantified and highly speculative at this time.

Acknowledgements

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